SPATIAL DEPENDENCE OF THE LOCAL DIFFUSION COEFFICIENT MEASURED UPSTREAM
OF THE NOVEMBER 12, 1978 INTERPLANETARY TRAVELING SHOCK

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1. Introduction. Characteristics of suprathermal particles accelerated
by quasi-parallel interplanetary traveling shocks have been generally
explained in terms of a first order Fermi mechanism (e.g. see review in
ref. 7). Such models require diffusive scattering of particles upstream
of the shock. This scattering is characterized by a local diffusion
coefficient, κ, which is determined by the local power density of waves
in the upstream region as described by Lee (7). A number of studies
have investigated the behavior of κ of $\lesssim 1$ MeV upstream ions close to
interplanetary shocks. Scholer et al. (8) have used results of first
order Fermi shock acceleration theory (e.g. ref. 1) to derive the
diffusion coefficient and its energy dependence from the measured
gradient of the upstream particle intensity. Van Nes et al. (9), using
the same approach, obtained the spatial and energy dependence of κ for 3
interplanetary shocks over a more extended energy and distance range.
Klecker et al. (6) deduced the spatial dependence of κ in the upstream
region for 30 and 130 keV protons from the measured first-order
anisotropies and intensity gradients.

In this paper we examine the dependence of the diffusion coef-
ficient of suprathermal upstream protons on distance from the November
12, 1978 interplanetary traveling shock using a different approach.
Unlike previous studies our method, which is based on measurements of
particle streaming and intensity gradients, does not rely on predictions
of shock acceleration theories or require first-order expansions. We
have chosen to examine the local spatial variations of κ upstream of the
November 12, 1978 shock because the characteristics of this quasi-paral-
lel shock have been extensively studied (e.g. ref. 5), and also because
of its favorable geometry (i.e. B field nearly radial). The initial
results of this study have been reported by Gloeckler et al. (3).

2. Instrumentation and Method of Analysis. For this study we use the
counting rate data from the University of Maryland/Max-Planck-Institut-
Garching ULECA sensor (see ref. 4 for details) on ISEE-3 which was
placed in a halo orbit at a radial distance of ~230 R_E upstream of the
earth. Of relevance to the present discussion are the capabilities of
the electrostatic deflection vs energy ULECA sensor to reliably separate
protons from alpha particles and to determine their differential inten-
sities in three energy bands centered on energies $\bar{E}$ of 33, 66 and 132
keV/e, and respective band widths $\Delta E/\bar{E}$ of 20, 27 and 37%. The sensor
has a 60° fan-like acceptance aperature with its wide angle in a plane
perpendicular to the ecliptic. The three proton counting rates are
available every 128 sec in each of eight 45° sectors of the ecliptic
plane.

For the present analysis we use the 33 and 66 keV sectored proton
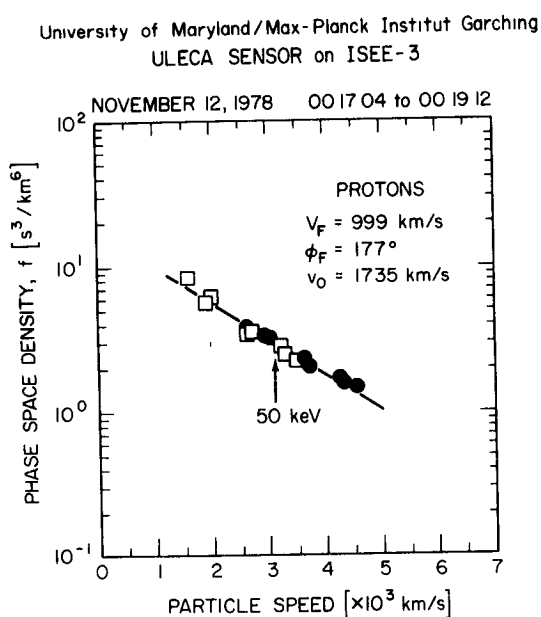counting rate data to derive the proton distribution function, f, in the

University of Maryland/Max-Planck Institut Garching
ULECA SENSOR on ISEE-3

NOVEMBER 12, 1978   00 17 04 to 00 19 12

PROTONS

V_F = 999 km/s
ϕ_F = 177°
v_0 = 1735 km/s

50 keV

PHASE SPACE DENSITY, f $[s^3/km^6]$

PARTICLE SPEED $[\times10^3$ km/s$]$

Figure 1. Rest frame proton phase space density, f(v). For V_F = 999 km/s and ϕ_F = 177° segments of f(v) from the 33 keV proton rate channel (open squares) and the 66 keV channel (solid circles) join smoothly to form a common spectrum.

frame of reference (rest frame) in which f is assumed to be isotropic, and find the velocity, $\vec{V}_F$, of that rest frame relative to the spacecraft. We follow the technique of Gloeckler et al. (2) for mapping the sectored counting rate data into segments of the rest frame distribution function f(v), where v is the particle speed in the rest frame, making use of the invariance properties of f. When the proper rest frame velocity, $\vec{V}_F$, is chosen, the two segments of f(v) join up and the resulting spectrum becomes smooth, as shown in Figure 1. We note in particular that our method requires no prior knowledge of the shape of the rest frame energy spectrum nor need V_F/v be small.

3. **Observations.** Using a least-squares technique we derive for each available 128 sec interval the rest frame velocity and the rest frame distribution function (over a range of particle speeds from ~1000 to 5000 km/s). Figure 1 shows an example of a 128 sec averaged distribution function f(v) obtained ~ $4 \cdot 10^{10}$ cm upstream of the shock. We note that the shape of f(v) tends to be between that of a pure power law and an exponential, and that the spectrum becomes harder with distance from the shock (3). In the present analysis an exponential form is assumed and the e-folding speed, v_0, is computed from a linear fit to the data as shown in the figure.

In Figure 2 we plot the derived speed, V_F, (solid circles) and direction of motion, ϕ_F, (upper panel) of the suprathermal proton rest frame for each available 128 sec interval as a function of time as the shock is approached. Notice that the direction of $\vec{V}_F$ is generally within ~10° antisunward. Also shown is the sum of the solar wind, V_{SW}, and Alfvén, V_A, speeds taken (or derived) from data published in (5). While far ahead of the shock V_F exceeds $(V_{SW} + V_A)$ by as much as 1000 km/s, close to shock this difference is about a few hundred km/s, and behind the shock the two velocities are the same within experimental errors, implying pure convention at a speed equal to the sum of solar wind and Alfvén speeds. If we interpret the difference between the speeds V_F and $(V_{SW} + V_A)$ upstream of the shock to be the diffusive streaming of suprathermal ions along the magnetic field B (nearly radial for this shock) which results from the observed upstream particle density gradient, the local diffusion coefficient along B, $\kappa_\parallel$ (r_i,v) at a distance $r_- = (t_{sh}-t_i)V_{sh}$ from the shock (V_{sh} and t_{sh} are the shock

speed and arrival times respectively) may be related to quantities measured at r_i as follows:

$$(1) \quad \vec{S} = 0 = [\tfrac{1}{3} v (\tfrac{\partial f}{\partial v})]*\vec{e}_B \cdot [\vec{V}_F(v)-(\vec{V}_{SW}+\vec{V}_A)] + \kappa_{\parallel}(r_i,v)*\vec{e}_B \cdot \vec{\nabla}f(v).$$

$\vec{S}$ is the differential streaming (which in zero is the particle rest frame), and $\vec{e}_B$ is the unit vector along $\vec{B}$. Since for the November 12, 1978 shock $\vec{B}$ and $\vec{V}_{SW}$ were nearly radial, and assuming that $\vec{V}_A$ was directed along $\vec{B}$ in the upstream region, and that f(v) has an exponential dependence on v with e-folding speed v_0, eq. (1) may be simplified to

$$(2) \quad \kappa_{\parallel}(r_i,v) = [\tfrac{v}{3v_0}]* [\tfrac{256 \cdot 10^{10}}{\ln(f_{i+1}/f_{i-1})} V_{sh}]* [V_F-(V_A+V_{SW})].$$

To obtain κ at a distance r_i upstream of the shock values for v_o are obtained from the slope of the ith distribution function, and the particle density gradient is determined from the neighboring values of f at v = 3100 km/s (50 keV). V_F and $(V_A + V_{SW})$ are those plotted in Figure 1 at times t_i related to r_i by $r_i=(t_{sh}-t_i)V_{sh}$, where we used values for V_{sh} of 612 km/s and t_{sh} of 0:28:18 as given in (5).
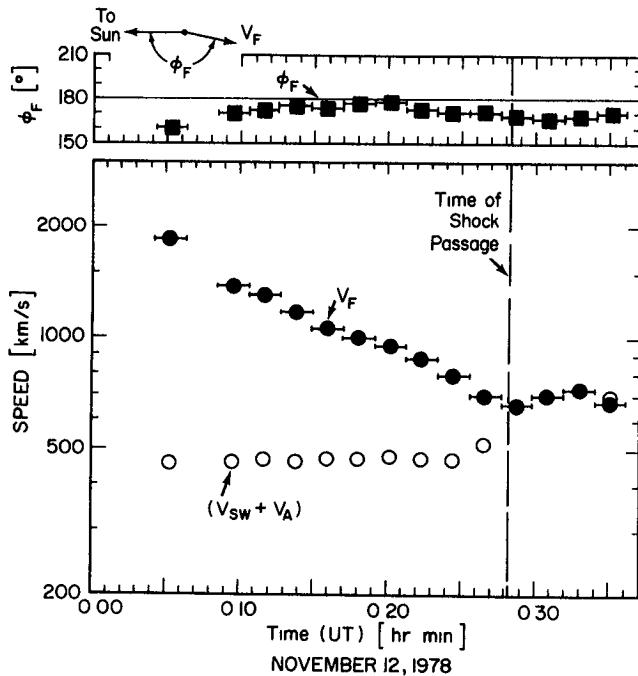

Figure 2. Speed and direction of motion of the rest frame (solid symbols) and the solar wind plus Alfvén speed $(V_{SW} + V_A)$ vs time before and immediately after shock passage. The difference between V_F and $(V_{SW} + V_A)$ is interpreted in terms of diffusive streaming. Behind the shock $V_F \simeq (V_{SW} + V_A)$ implying pure convection of 50 keV protons at that speed.

4. Spatial Dependence of $\kappa_{\parallel}$. In Figure 3 we show values of $\kappa_{\parallel}$ for ~ 50 keV protons as a function of distance from the shock, where $\kappa_{\parallel}$ is computed using eq. (2). The uncertainties shown come primarily from inaccuracies in determining the local density gradients. We note that there may be systematic errors ($\lesssim 30\%$) in the values of κ resulting from using the simpler eq. (2) rather than eq. (1) which incorporates vector quantities. Consistent with expectations (7) we find that κ increases exponentially from a value of $\sim 7 \cdot 10^{17}$ cm^2/s near the shock to $\sim 2.5 \cdot 10^{18}$ cm^2/s at $\sim 4.5 \cdot 10^{10}$ cm from the shock with an e-folding distance of $3.4 \cdot 10^{10}$ cm. What is surprising is the subsequent decrease (again exponential, with e-folding distance of $\sim 1.1 \cdot 10^{10}$ cm) in

the value of κ with distance from the shock.

5. Discussion and Conclusions. The factor of ∼ 4 increase in κ over a distance of ∼ 4.5·10¹⁰ cm is consistent with a comparable decrease in the power spectral density of waves at $2 \cdot 10^{-2}$ Hz (see Fig. 8 of ref. 7).
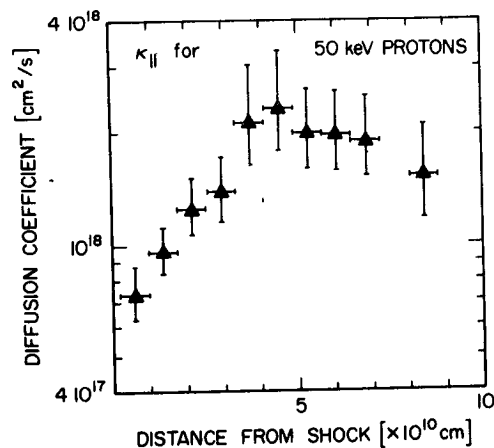

Figure 3. Spatial dependence of $\kappa_\parallel$ on upstream distance from the shock.

The value of $7 \cdot 10^{10}$ cm²/s of $\kappa_\parallel$ (50 keV) near the shock is in excellent agreement with prediction (for this shock) based on a self-consistent theory for wave excitation and particle acceleration upstream of interplanetary shocks (7). Our values of κ and its spatial dependence are also in qualitative agreement with those reported in (6,9). What is puzzling is the decrease of $\kappa_\parallel$ (50 keV) at larger distances which is not predicted by current theory. To pursue this point further we computed $\kappa_\parallel$ (100 keV) following the procedure outlined above but now using the 66 and 132 keV proton counting rate data. We found that the rest frame speeds V_F characteristic of ∼100 keV protons are smaller than those shown in Figure 1 for 50 keV protons.

Ratios of κ_{100}/κ_{50} were determined to be ∼3.0, 1.2 and 1.8 near the shock, at r = 4·10¹⁰ cm and 8·10¹⁰ cm respectively. Assuming a simple power law dependence of κ on particle energy these values correspond to $\kappa \propto E^{+1.6}$, $E^{+0.26}$, $E^{+0.85}$ respectively. We therefore conclude in agreement with (9) that one cannot characterize the energy dependence (or the spatial dependence) of κ in a simple way. Our results indicate an increase in the wave power density beyond r ∼ 5·10¹⁰ cm and in general a more effective scattering of 50 keV protons compared to 100 keV protons. This hypothesis can be checked using local wave power spectrum measurements as a function of distance from the November 12, 1978 interplanetary traveling shock.

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